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This issue of the Meteorological Magazine is dedicated to three papers on the topic of mesoscale weather forecasting. The first two describe the current status of two research programs which, if successful, would lead to a large amount of additional guidance being available for local forecasting.

The third paper examines in more general terms some of the opportunities and challenges in making use of such guidance. It presents one view of how forecasting geared to periods of 12 hours ahead or less might develop, particularly at outstations. It is not a blueprint for the future and depends upon forecasts from the FRONTIERS* system and from the mesoscale numerical model achieving an accuracy and precision which have not yet been demonstrated, and which will require at the very least a further period of intensive research effort. The real developments are likely to be different from those envisaged in the paper, but the general trend towards the kinds of equipment and techniques which the authors describe is almost certainly correct. It must be expected that they will have a substantial influence at meteorological stations within the next few years.

*FRONTIERS: Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite

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FRONTIERS five years on

By K. A. Browning and K. M. Carpenter

(Meteorological Office Radar Research Laboratory, Royal Signals and Radar Establishment, Malvern)

Summary

Five years have elapsed since FRONTIERS was first written about in the *Meteorological Magazine*. The FRONTIERS program is a strategy for using a radar network together with Meteosat to provide meteorological offices and other users with precipitation nowcasts, i.e. detailed descriptions of the current distribution of precipitation plus forecasts up to several hours ahead obtained by extrapolation. An important part of this program is the involvement, within an otherwise highly automated system, of a forecaster who can exercise judgement by means of a centrally-located interactive display system, or work station. The purpose of this paper is to describe the current status of the FRONTIERS program.

1. Introduction

The Meteorological Office has been using an integrated network of radars with remote colour displays of composited data as a forecasting aid for some years. It is also developing ways of processing and displaying Meteosat cloud imagery in the same format as the radar pictures. The background to these programs was reviewed by Browning (1980) and some recent examples of the operational utility of these products have been presented by Booth (1984).

Quite early in the development program it became apparent that the usefulness of the radar network pictures is often impaired by errors, many of which are meteorological in origin and difficult to correct objectively. The need was felt for a means of exercising effective quality control and analysis in real time. Moreover, although the radar and satellite products were found to be very useful separately, it was considered that the limited coverage of the radar data was a major restriction that could be largely removed if ways were developed of combining radar and satellite data to provide analyses of precipitation over an area rather larger than the radar network. Given rainfall analyses of such a kind it would then be natural to derive ways of producing, on a regular basis, detailed forecasts for several hours ahead, by extrapolation of successive patterns of precipitation. It was with these aims in mind that the FRONTIERS program was conceived (Browning 1979).

The radar data used in this program are summarized in section 2. The satellite data used to extend the radar coverage, and the generation of forecasts, are outlined in section 3. Of the new techniques being used, the key element is the development of interactive methods whereby a forecaster can analyse and combine the radar and satellite pictures and generate forecasts directly on the screen of a colour monitor. The FRONTIERS interactive display system (Browning and Collier 1982), described in section 4, is intended to be operated as a central facility. The idea is that a forecaster in the Central Forecasting Office could exercise judgement in the processing of the radar and satellite imagery so that improved products could be sent to meteorological outstations and other customers using the same means as are currently being established to distribute the ordinary radar network pictures.

Two features distinguish the FRONTIERS interactive display system from other interactive systems in use by the meteorological community. The first is that FRONTIERS is designed to solve a single specific problem, the derivation of actual fields and forecasts of precipitation. This has enabled us to design the system in detail at an early stage. The second is that the system is genuinely interactive and not merely a very modern display device. Using the FRONTIERS display the operator actually changes the data directly, just as if he were rubbing out data on a piece of paper and sketching in fresh information.

The FRONTIERS interactive display is, at the time of writing (March 1984), still undergoing pre-operational trials and development. The network of radars on which it depends, however, is close to being fully operational, and we shall review the current status of this next, before going on to consider the actual FRONTIERS system in more detail.

2. The weather radar network

Fig. 1 shows the network of radars available to the Meteorological Office as it is expected to be by autumn 1984. The network is a mixture of C-band (5.6 cm) and S-band (10 cm) radars with beam widths of one or two degrees. The first four radars to be installed (numbers 1 to 4 in the diagram) have all been in regular operation since 1980 or earlier. The data processing required to achieve the composite radar display is described by Collier (1980). Each radar in the network has its own on-site minicomputer which accepts the raw radar data, applies various corrections, and sends the data over dedicated telephone lines to a number of locations, including Malvern where another minicomputer automatically generates an overall radar composite picture. The networking computer used for this purpose, now referred to as Radarnet, is expected to be moved to Bracknell and backed up as a fully operational system during 1985. At present the composite picture is derived on a 256 × 256 grid of 5 km squares, and a 128 × 128 array of 5 km squares is extracted covering the dashed square in Fig. 1. The pictures are disseminated for presentation on special-purpose (Jasmin) displays with limited action-replay facilities. These are currently being made available to an increasing number of forecasting offices.

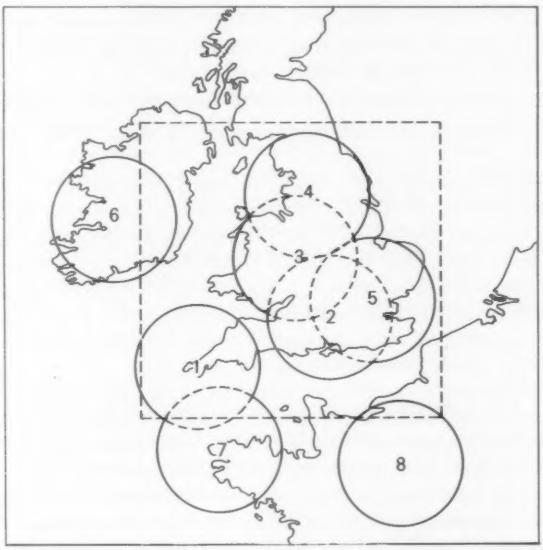

Figure 1. Coverage of weather radars and radar-compatible Meteosat data to be used in FRONTIERS as from autumn 1984. Radars are at (1) Camborne (Cornwall), (2) Upavon (Wiltshire), (3) Clee Hill (Shropshire), (4) Hameldon Hill (Lancashire), (5) Chenies (Buckinghamshire), (6) Shannon (Republic of Ireland), (7) Brest (France), and (8) Dammartin en Goelle (France). The circles show the range of generally useful coverage for each radar — 150 km (i.e. between the so-called quantitative limit of 75 km and the maximum range of 210 km). The solid outer frame is the boundary of Meteosat imagery normally used in the FRONTIERS display and the dashed inner frame the area of the radar network routinely available on Jasmin displays.

During summer 1984 several more radars were being added to the network as part of collaborative projects. Radar 5, covering the London area, is a new unmanned radar. It resembles radar 4 which was established as part of the successful North West Weather Radar Project (Collier *et al.* 1980). Data from radars 6 to 8 are available as part of the European Weather Radar Network Project (COST 72 1982) or through bilateral agreements with neighbouring countries. Further extension of the network is under active consideration both as part of national plans involving the Meteorological Office in collaboration with other parties, especially the water industry, and also as an extension of the international exchanges already mentioned.

In order to display data from the extended radar network shown in Fig. 1 without degrading resolution, a new user display will be required to succeed the existing display. A replacement display system has been specified and two prototypes are expected to be available for evaluation by 1985. In addition to being able to display products available directly from the network computer, the new display will be able to replay long sequences, zoomed or unzoomed, of several kinds of pictures which may be generated centrally using the FRONTIERS display. The maximum area of coverage of these pictures would be a 256 × 256 array of 5 km squares, approximately as shown by the outer frame.

3. Products from FRONTIERS

The new forms of data that could be generated using a centrally-located FRONTIERS interactive display include:

Product I:	quality-controlled radar rainfall analyses,
Product II:	rainfall actuals over a large area derived from a combination of radar network and Meteosat imagery,
Product III:	rainfall forecasts for a period of say one to six hours ahead,
By-product IIa:	registered (i.e. accurately located) Meteosat imagery in the same format.

Such products, given an operational system, would probably be generated at 30-minute intervals and distributed with a delay of 20 to 40 minutes. This is to be compared with pictures every 15 minutes distributed with a delay of about 5 minutes for radar composite pictures obtained as at present from the Radarnet computer. Clearly the added value in the FRONTIERS products can only be obtained with some sacrifice of speed. Indeed we suspect that, when FRONTIERS becomes operational, some users would wish to continue to make use of the automated Radarnet product, with all its defects, because it is available so quickly, in addition to using the slightly delayed FRONTIERS products. We shall now consider the FRONTIERS products in more detail.

The cycle of operations carried out by the forecaster at the FRONTIERS interactive display is constrained by the 30-minute cycle for the reception of B-format digital Meteosat data. At present the processed cloud imagery is available in the FRONTIERS display within 20 minutes or so of the nominal observation time, i.e. 15 minutes after the corresponding radar pictures. There are three main stages in the cycle of operation corresponding to the generation of Products I, II and III, and the present approach is to allow the operator about 10 minutes for each. In round figures this means that the first stage starts at $T+10$ minutes, with Product I available for dissemination at $T+20$ minutes. The second stage starts at $T+20$ minutes, with Product II available at $T+30$ minutes. The third stage starts at $T+30$ minutes, with Product III available at $T+40$ minutes.

In more detail, the FRONTIERS operator carries out a selection of the following steps during the generation of Product I: deletion of unreliable radars from the composite picture; deletion of spurious

echoes unrelated to precipitation; monitoring and modification of bright-band (melting level) corrections derived at radar sites; designation of rainfall types to allow appropriate calibrations and range-dependent corrections to be applied; adjustment of calibration of any suspect radars in the light of available ground truth and space/time continuity; incorporation of likely orographic rainfall enhancement by specifying the nature of the low-level airflow.

The generation of Product II involves three main steps using the Meteosat cloud imagery. The first step is to register the imagery. The Meteosat pictures used in FRONTIERS have the distortions due to the viewpoint in space removed objectively and they are displayed in the same National Grid format as the radar pictures. However, they are not always positioned accurately and so it is necessary to check the registration by comparison with a coastline overlay. The second step is to transform the imagery objectively to a first-guess rainfall pattern using algorithms that relate surface rainfall to infra-red radiance and, when available, visible brightness (Lovejoy and Austin 1979). The FRONTIERS operator can select either universal relationships derived for different cloud types, or current relationships based on contemporary co-located radar data. The third step is to apply the rainfall pattern estimated objectively from Meteosat to extend the rainfall analysis beyond the area covered by the radars, intervening subjectively to delete or extend areas of rain inferred from the satellite so as to obtain consistency with the radar-derived patterns and any ground truth available from other sources. There are times, especially on occasions of widespread cirrus, when the satellite guidance is positively misleading as a first guess of the rainfall pattern. The operator then has to disregard much of the detail of the satellite imagery and build up his own analysis in an almost entirely free-hand manner. The extension of coverage of estimated rainfall using Meteosat data, although clearly qualitative, is nevertheless valuable in that it sets the more accurate radar data in a broader synoptic context and gives advance warning of possible rain clouds approaching from data-sparse areas over the sea.

In the derivation of Product III, the rainfall forecasts, the first step is for the computer to divide the analysed fields of rain into a number of clusters of contiguous rain areas. It then compares the position of each cluster with that obtained 30 minutes earlier and derives an extrapolation forecast on the basis of the resulting set of displacement vectors. This can be done entirely automatically but it has been found (Browning *et al.* 1982) that subjective forecasts based upon the same principles are more accurate and reliable. This is partly because a forecaster can recognize and allow for deficiencies in the initial data, as in the generation of Product I. It is also because the objective extrapolation algorithms now being used do not perform well in other than simple situations. Thus at present the best results are usually obtained by determining the velocity of rainfall clusters subjectively, e.g. by using the Lagrangian replay facility described in section 4. In essence the FRONTIERS computer takes the burden of calculation away from the operator but allows him to make a variety of logical choices or to modify forecasts that have been calculated.

4. Technical aspects of the FRONTIERS interactive display system

The FRONTIERS interactive display system is being developed jointly by the Meteorological Office and Logica Ltd as a central node within a distributed computer network. The FRONTIERS computer is a DEC VAX 11/750 supported by two RM80 discs and a TGU 77 tape drive. Other centrally-located minicomputers processing the radar network and Meteosat imagery pass data to it via high-speed (56 000 bits per second) DMR 11 interfaces. The FRONTIERS computer provides images to two Ramtek 2455 display systems which support two colour monitors and a joystick. As shown in Plate I, (page 298) the operator interacts with the imagery via one of the monitors which is fitted with a touch screen; this is sensitive to touch and is able to transmit coordinate information to the FRONTIERS computer. The facility shown in Plate I is referred to as a work station. A data tablet is also available

(Houston Instruments Hipad digitizer) which can be used interchangeably with the touch screen. The second monitor is there to provide supporting information and is not used interactively. Images on both monitors can be replayed at six frames per second. The response time for calling up an image is about two seconds.

A design constraint placed on the FRONTIERS display is that it should be easy for a forecaster to use without special training or aptitude in computer operation. The operator has to be allowed to concern himself solely with the meteorology. Accordingly keyboards, codes and complicated instruction sets are avoided. This has been achieved by basing the system on menus that are displayed as required, and from which the operator can choose the appropriate action by touching the screen. The FRONTIERS computer supports two VDUs (Visual 100s) fitted with touch screens for this purpose. A typical task is one in which an area of radar echo needs to be deleted. The echo in question is defined by touching the appropriate menu item and drawing a line round the echo on the colour monitor. Similarly, the displacement needed to position a satellite image accurately can be achieved by touching the menu and then using the joystick to bring the image into correspondence with a coastline overlay. Where the operator has a choice of device, e.g. between the colour monitor touch screen and the data tablet, he makes the choice simply by using the preferred device.

Another example of the sort of operation possible using the FRONTIERS interactive display is provided by the Lagrangian replay facility, referred to earlier. As part of the forecasting sequence the computer identifies areas or 'clusters' of rainfall and automatically calculates their velocity. The operator can modify the clusters by amalgamating or subdividing them and can also modify the velocities that have been calculated. There are several ways in which the operator can determine velocity and one of these is by means of the Lagrangian replay. When the operator requests this facility he touches a feature of the rainfall pattern at the beginning and end of the sequence he wishes to replay. Touching the same feature twice defines its velocity. The system then replays the full sequence in a Lagrangian frame of reference, i.e. with the velocity of the feature subtracted. If the feature still moves a little, the operator can use the joystick to modify the velocity until he is satisfied that the image is truly stationary in the Lagrangian frame. Once this has been achieved, the velocity of the feature of interest is accurately defined.

5. An example of the use of the FRONTIERS interactive display system

Plates II to VIII, (pages 298 and 299) depict the FRONTIERS display at different stages during the interactive processing of the data for 10 GMT on 9 December 1983 when a low-pressure system was centred over Wales.

Plate II shows the radar network display derived automatically from radars 1 to 4 (Fig. 1). The circles show the maximum range of each radar. By replaying a time sequence of pictures the FRONTIERS operator was able to ascertain that the echoes in the eastern parts of the coverage of radar 2 were spurious, and Plate II shows the line he has drawn to demarcate them. The operator then deleted all the spurious echoes and the resulting cleaned-up display is shown in Plate III.

Plate IV shows Meteosat infra-red imagery over the whole area corresponding to Plate III. This immediately enables the forecaster to make more sense of the radar rainfall pattern in Plate III. The relationship of the rain to the swirl of cloud and the low-pressure centre is obvious. The irregular western boundary of the radar echo over the Irish Sea, for example, is due to the range limitations of the individual radars.

Plate V shows a combined image in which the operator has displayed Meteosat data everywhere except within the area of good radar coverage. Because the visible imagery was poor at this hour the operator has had to make the best use he could of the infra-red imagery alone. On this occasion he has

subjectively selected essentially a single threshold to obtain reasonable continuity between the radar and satellite data. Above this threshold he has displayed most of the satellite data as light blue, corresponding to light-to-moderate rain. However, he knew from surface reports in Ireland and Scotland that any precipitation falling from the deck of high cloud was evaporating before reaching the ground in some of those areas, and Plate V shows the line he has drawn on the display to mark the probable boundary of surface rain (the analysis over the North Sea and France is uncertain). The operator then deleted the non-raining cloud and allowed the computer to reduce the resolution from 5 to 20 km, as shown in Plate VI, in readiness for the computation of objective forecasts.

Plate VII shows the computer-generated analysis of the rainfall pattern in terms of clusters and cluster velocities: different rainfall clusters are identified by different colours and each cluster is assigned a displacement vector. Replay of the previous series of actuals showed the operator that, although most of the clusters were indeed travelling in a southerly direction as indicated by the vectors, the blue cluster over the Midlands was travelling towards the east. Accordingly he redefined its velocity subjectively using the Lagrangian replay facility. In fact this blue cluster is seen to be contiguous with the yellow cluster and the operator had first to intervene subjectively to override the computer analysis which initially had portrayed it simply as part of the large yellow area. Given the modified rainfall clusters and vectors, the final stage was for the computer to derive a set of forecast rainfall patterns by extrapolation of the 10 GMT analysis. One of these forecasts, for $T + 2$ hours (i.e. 12 GMT), is shown in Plate VIII.

6. Concluding remarks

The FRONTIERS interactive display system was designed to solve a very specific problem, the analysis and very-short-range forecasting of precipitation. This has enabled us to anticipate the questions the forecaster would face and the manner in which he would seek to answer them. Each half-hour the forecaster operating the system has to consider three broad problems, i.e. the use of the radar data to estimate surface rainfall, the use of Meteosat data to extend the coverage, and the generation of extrapolation forecasts. This imposes a stringent timetable and it is this fact as much as the general need for efficiency and 'user-friendliness' that has led to the facilities described.

An important aspect of the mode of operation of the FRONTIERS display is that it is menu-based. In normal real-time operation the forecaster using the system is taken through a (more or less) fixed sequence of menus in a (more or less) predetermined order. However, the architecture is so designed that as part of the development of the system it is easy to alter the menus and the logical relationships between them. The FRONTIERS interactive display system is to be moved from Malvern to Bracknell along with the Radarnet and Meteosat computers during 1985. This will not mark the end of the development stage, however. As in the case of the existing forecasting system based upon numerical–dynamical methods, we can expect the development of the FRONTIERS nowcasting system to be a continuing process over a period of many years. It is to be hoped that regular use, backed up by an active research and development program, will help us to achieve a steady improvement in the quality of mesoscale precipitation guidance over the coming decade.

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The Meteorological Office mesoscale model: its current status

By B. W. Golding

(Meteorological Office, Bracknell)

Summary

A numerical forecast model with very fine resolution is being developed as a short-period forecast tool to give detailed guidance on local weather up to a day ahead. The processes represented in the model have been specially developed to take account of the scales represented. Surface synoptic reports are incorporated into the initial data to give mesoscale detail on boundary layer and cloud variables. A weekly trial of the complete system has started and is giving encouraging results.

1. Introduction

Numerical models in current operational use give valuable guidance to forecasters on the broad-scale atmospheric structure. A grid length of about 150 km is used for global predictions and half that for the regional model covering the North Atlantic and Europe. However, even this latter model cannot represent the topographic differences between parts of the United Kingdom which are important for short-period forecasting. A mesoscale numerical forecast model with very fine resolution is being

developed to tackle this problem with the aim of providing guidance to forecasters on the local variations of weather in the period up to a day ahead. This model will be closely tied to the regional model through its boundary conditions so it must be seen as a sophisticated tool for adding detail to the predictions of the coarser models. In particular it will not be able to correct timing errors in systems that are passed through the boundaries. On the other hand, in slow-moving situations the topographically-induced effects should be well forecast and should be of considerable help to the outstation forecaster. It is widely recognized that model predictions of mesoscale systems that are not forced by topography will be difficult. However, the errors will often be in timing or location in the same way that regional scale models predict realistic development of secondary depressions but often at the wrong time or place. It may also be that much of the mesoscale variation in weather from larger-scale systems is actually induced by topographic variations, perhaps through the surface temperature or moisture. In these cases the added detail will be of considerable value provided that the regional model has correctly predicted the large-scale evolution. In these situations an important task to be performed after the forecast will be to apply gross timing or development corrections which have become apparent through consideration of other observations and forecasts. This will involve the sort of techniques discussed by Browning and Golding (1984). In the present paper, the remaining sections will describe the model formulation, the methods currently used for preparing the initial data, and some recent results.

2. The forecast model

The model is planned to cover the British Isles with a grid length of 10 km but currently uses a 15 km grid length (see Fig. 1). With this resolution a reasonably faithful representation of the orography can be given, and the coastline, indicated by the zero contour in Fig. 1, has a realistic shape. The mountain ranges are still somewhat lower than reality, e.g. the Cairngorms reach 750 m rather than the observed 1200 m. Also the valleys which dissect them are not represented and so their local effects on the weather of cities like Sheffield, for instance, cannot be accounted for. A grid length of under 5 km would be needed to represent such features and is not feasible on a national basis with current computers. Their effects will therefore have to be added to the model guidance by the forecaster.

The basic dynamical equations used by the model have been described in Tapp and White (1976) and Carpenter (1979). In most respects they are the same as those used in the lower-resolution operational models. Important differences are that hydrostatic balance is not imposed and that the vertical co-ordinate is height above land surface rather than a pressure-based coordinate. Non-hydrostatic effects are important for small-scale thermally-driven circulations while the height coordinate is advantageous for prediction of near-surface effects. The vertical structure of the model is shown in Fig. 2 for the current version with 16 levels. The lowest level is at 10 m and the spacing increases linearly from 100 m to 1500 m at the top. The highest level at 12 010 m is in the stratosphere. This arrangement gives 5 levels in the lowest kilometre, and, when expressed in terms of the standard atmosphere, an almost constant spacing of 60 mb from there up to the tropopause.

In large-scale models, many of the weather-producing processes occur at scales much smaller than the model's resolution. They are parametrized in terms of scales that are resolved by assuming that they can be represented by the effects of a statistically homogeneous and stationary ensemble covering a grid square. These models ignore the presence of processes at intermediate scales. It is these intermediate scales that are explicitly forecast by the mesoscale model. Smaller-scale processes must still be parametrized and in many cases the same techniques can be applied as in larger-scale models. However, deep convection occurs on scales close to the model resolution so the statistical assumptions are not tenable in this case. In the following sections descriptions of these parametrizations are given under the headings of boundary layer, layer cloud, and convective cloud processes.

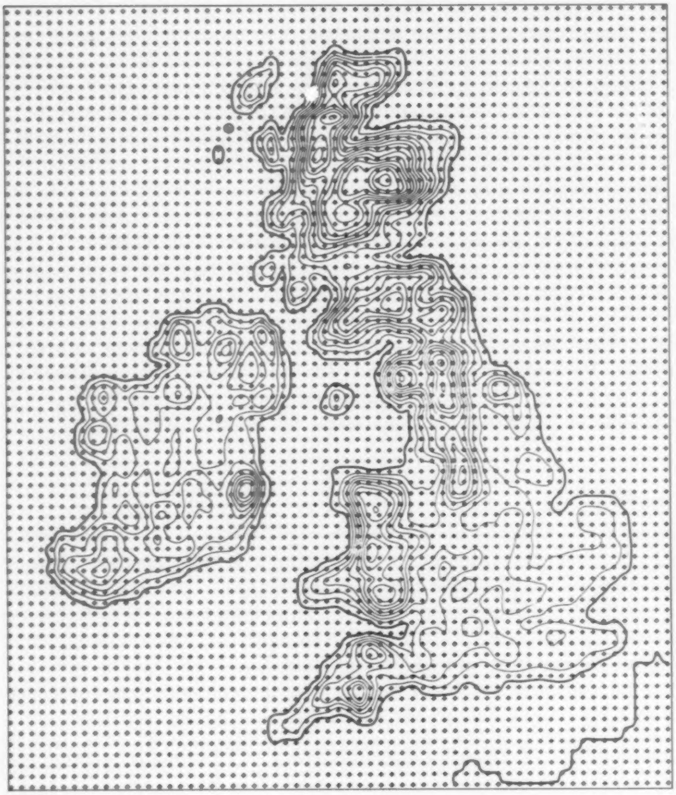

Figure 1. Model domain and orography. The grid points have a 15 km spacing and the contour interval is 50 m. The bold contour is at zero metres and indicates the model coastline.

(a) *Boundary layer processes*

The processes involved are illustrated schematically in Fig. 3. They may be divided into three groups: radiation, turbulent transport in the atmosphere and conduction in the ground. All three are controlled by the characteristics of the ground, e.g. its wetness, reflectivity, conductivity and porosity, and the vegetation present. At present two characteristics, the albedo and soil conductivity are specified as fixed over all land areas. However two others, the roughness length (Z_o) and the surface resistance to evaporation, can be varied. Over the sea the latter is zero and roughness is related to wind speed through Charnock's formula (Charnock 1955):

$$Z_o = \mathrm{k}g^{-1}u_*^2$$

where g = acceleration of gravity, k = 0.035 and u_* is calculated from the 10-metre wind, using the

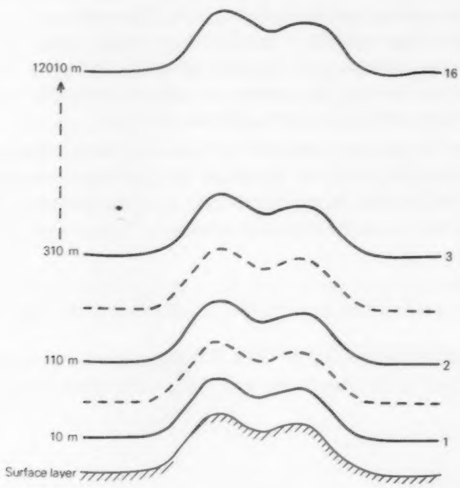

Figure 2. Vertical structure of the model. The vertical co-ordinate is height above ground and there are 16 levels from 10 m to 12 010 m. Wind, pressure, temperature, relative humidity and cloud are carried at the main levels indicated by solid lines. Vertical velocity and turbulent kinetic energy are carried at intermediate levels.

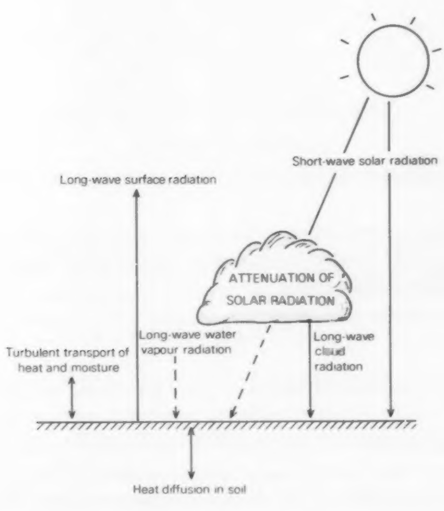

Figure 3. Schematic diagram of processes involved in the surface heat balance of the model.

previous timestep's drag coefficient. Over land, roughness length is at present fixed at 0.1 m but variations for urban and forest areas will be included soon. The resistance to evaporation is allowed to vary with time over land. The value at night is much greater than during the day to model the effects of darkness on the transpiration of plants, and it is zero when rain is falling or dew is forming. Clearly a desirable improvement will be for this parameter to remain zero after rain has fallen until it has evaporated, percolated into the ground, or run off into rivers.

Most of the heat gain at the surface comes from solar radiation. This is strongly affected by the presence of clouds in the atmosphere and is modelled by applying a transmission function (T) which depends on the integrated density of forecast cloud through a column of the atmosphere. The function has been fitted to data obtained from the radiation scheme of Slingo and Schrecker (1982) and has the form

$$T = \exp \{ -7.9\ W^{0.5} / (1.84 + \cos^2 \alpha) \}$$

where W is the total liquid water path in kg m^{-2} and α is the solar zenith angle. The variation of T with W, for $\cos \alpha = 0.4$, is shown in Fig. 4. Clouds also emit long-wave radiation and it is the balance between

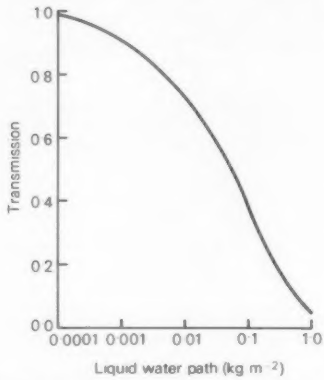

Figure 4. Transmission of solar radiation by cloud as a function of total liquid water path.

this and the radiation emitted by the ground which determines the surface temperature in overcast conditions. The cloud emission (L) is again dependent on the total liquid water path (W) and is based on a scheme of Lind and Katsaros (1982) giving

$$L = \sigma \{ 1 - \exp (-70\ W) \} T_c^4 .$$

where σ is the Stefan–Boltzmann constant and T_c is the cloud-base temperature.

Heat conduction in the ground is crudely modelled by predicting the temperature of a single level in the ground. This varies slowly depending on its difference from the surface temperature.

The final component of heat balance at the surface is turbulent diffusion through the lowest layers of the atmosphere. In the model, transport between the surface and the first level at 10 m is modelled using the Monin–Obukhov similarity theory to calculate the mixing coefficient. A full description of the formulation is given in Carpenter (1979). The surface resistance to evaporation, defined above, is

important here in determining the relative transports of sensible heat and of moisture. Above the 10 m level the mixing coefficients are determined from a forecast parameter, the turbulent kinetic energy (TKE), and a diagnosed one, the mixing length. The latter increases above the ground until it reaches an empirically-defined fraction of the boundary layer depth. The TKE is generated by shear and buoyancy and can also be transported. In particular, it can be diffused upwards from where it is generated near the ground to the boundary layer top, where the resultant entrainment of air from above is an important factor in the boundary layer evolution. The present formulation of these processes does not account for the reduced stability when saturation occurs. However, a revised formulation including its effects is under test and in particular should improve the prediction of stratus and stratocumulus cloud.

(b) *Layer cloud processes*

The processes involved in the layer cloud parametrization are depicted in Fig. 5 for a region of orographically-induced cloud. When moist air is cooled to saturation point in the model, condensate is

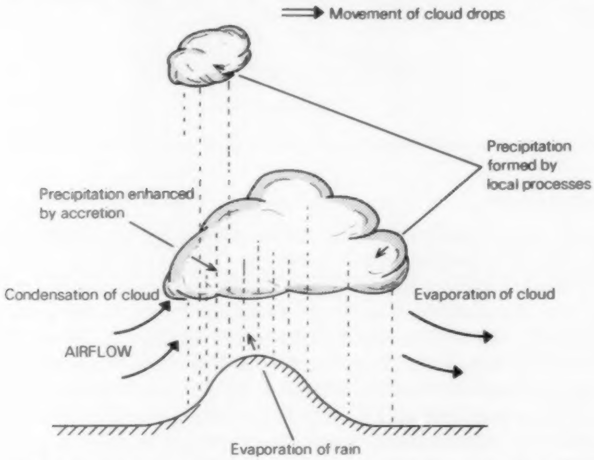

Figure 5. Schematic diagram of processes involved in the layer cloud parametrization. The wind is assumed to be blowing from left to right at all levels.

not immediately rained out as in most large-scale models, but is stored as cloud water. When enough has accumulated, it will precipitate. Meanwhile, it is transported by the wind and, if warmed, may re-evaporate. The precipitation process itself is based on a simplified version of a scheme by Sundqvist (1978). It has two components, a local production term and an accretion term.

$$\frac{dP}{dz} = \left(C_L + C_A P\,(z)\right)\ \left[1 - \exp\left\{-(m/C_M)^2\right\}\right]\ m$$

where m is the cloud water mixing ratio, $P(z)$ is the precipitation rate at height z and C_L, C_A and C_M are empirical constants. The exponential term merely ensures that for very low cloud water densities, no rainfall is produced. Above a threshold determined by C_M, the local production depends linearly on m and the accretion term depends on the product of m and P, the precipitation rate from higher cloud. The effect of the accretion term in enhancing the precipitation from 'seeder' clouds can be seen in Fig. 5. The

combined effect of the two terms for clouds of increasing depth but fixed cloud water mixing ratio is shown in Fig. 6. Below cloud base, precipitation is evaporated as it falls to the ground. No specific allowance is made for the physics of solid precipitation in the model. However, the cooling effect due to melting snow is included because of its importance in modifying the low-level temperature structure when surface temperatures are near freezing.

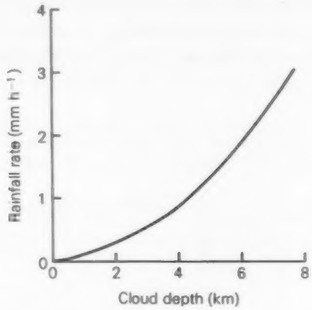

Figure 6. Rainfall rate as a function of total cloud depth for a fixed cloud water mixing ratio (0.6 g kg^{-1} in this example).

(c) *Convective cloud processes*

In large-scale models, cumulonimbus clouds are modelled by parametrizing the mean effect of a large number scattered throughout a general area of instability. This approach is inappropriate for a model with a grid length of the same order as the largest clouds and much smaller than a typical spacing between clouds in an area of instability. It is therefore necessary to model the processes in an individual cloud rather more carefully. The scheme used in the model attempts to do this but is still capable of considerable improvement. It is based on that described by Fritsch and Chappell (1980). Fig. 7 shows a schematic of the 'typical' cumulonimbus cloud used in the parametrization. An important departure from schemes used in large-scale models is that the cloud has a specified lifetime, much larger than the model timestep. Indeed a version currently being tested allows the cloud to move during its life. The details of the cloud's life cycle are not, however, modelled. Its growth, maturity and dissipation are all averaged out over its lifetime. A major problem for all cumulonimbus parametrizations is to determine the amount of cloud or, more specifically, the mass flux of air through the cloud(s). In the present case this is determined by the maximum deviation of the pseudo-adiabat of a parcel lifted from cloud base from the environmental temperature sounding. For a given depth of cloud, a standard mass flux is defined taking account of the observation that the aspect ratio of depth to area is of limited variability. If the temperature criterion would give a very tall, thin cloud, the aspect ratio criterion overrides this. Another difficulty in formulating a parametrization is to determine under what conditions a cloud will form. These are sensitive to the formulation of the boundary layer scheme and in the present model are determined by testing the stability to lifting of layers that have already been saturated, normally by upward turbulent transport of moisture.

Other details of the scheme are illustrated in Fig. 7. The updraught is modelled as an entraining plume with inflow below cloud base and outflow where the upward momentum created by buoyancy is reduced to zero. The downdraught is forced by precipitation drag and cools by evaporation below cloud base before spreading out in the lowest three layers, i.e. 460 m, of the model. The net mass flux from the updraught and downdraught is balanced by subsidence in the environment. Finally, air from the

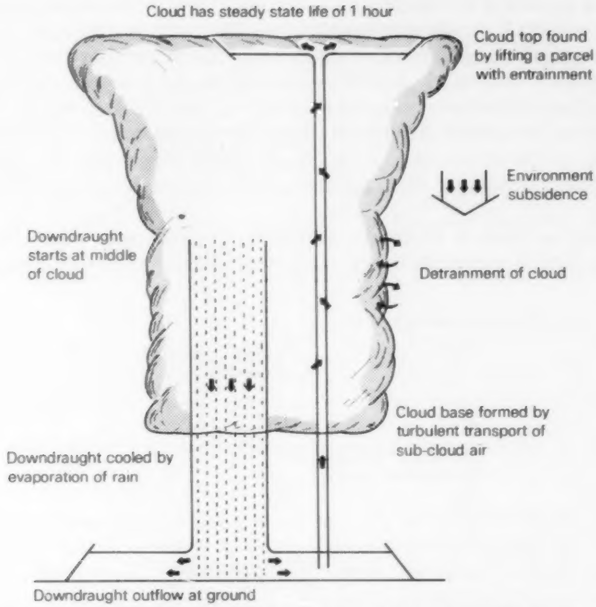

Figure 7. Schematic diagram of the cloud model used in the convection parametrization.

updraught and downdraught is mixed into the environment to simulate the dissipation process. Rainfall is determined as a proportion of the total moisture condensed in the updraught, the proportion having an empirical dependence on mean vertical shear and humidity. The remaining condensate is mixed into the environment with 60% from the 'anvil' and 40% from the lower layers of the cloud. An empirical formula is also used to relate the rain area to the mass flux and mean shear of the cloud so that local rainfall intensity can be diagnosed. Despite this sophistication, the scheme inherits many of the limitations of those in larger-scale models. Most important is the assumption that there is no net vertical mass flux in a grid column. This is reasonable for grid lengths of several hundred kilometres but incorrect for 10 km grid lengths. At present the scheme also lacks parametrizations of momentum transport and ice phase effects.

3. Initialization

The representation of the initial state of the atmosphere is of critical importance to the quality of forecast that can be expected from the model. As with large-scale models, the constraints of near-geostrophy must be satisfied if a stable forecast evolution is to be obtained. However, a short-range forecast model must also be correctly initialized with cloud if the temperature and precipitation are to be realistically forecast. Indeed, the atmosphere 'remembers' much of its initial state over a 12-hour period on many occasions and this contributes to the accuracy of subjective forecasts based on modified extrapolation procedures.

In the mesoscale model, the basic specification of initial conditions is obtained by interpolation of a short forecast (usually six hours) from the operational regional model. The regional model analysis is

not used since that is at present an interpolation from the global model analysis with a grid length of 150 km and having a very crude topography specification. The interpolation to the mesoscale model grid is a complex process since the models are based on different map projections, they have different vertical coordinates and different orography, and the mesoscale model has finer resolution. These initial conditions are then enhanced by the use of surface synoptic observations. At present the techniques used are purely objective but interactive facilities are being developed and it is intended that the human analyst will be able to influence the process at all stages (Browning and Golding 1984). The modifications are made in two stages. First, surface variables and then cloud variables are analysed and incorporated.

The use of surface variables is illustrated in Fig. 8. Temperature, relative humidity and wind observations are first used to correct the interpolated 10 m values of these variables. When a well mixed

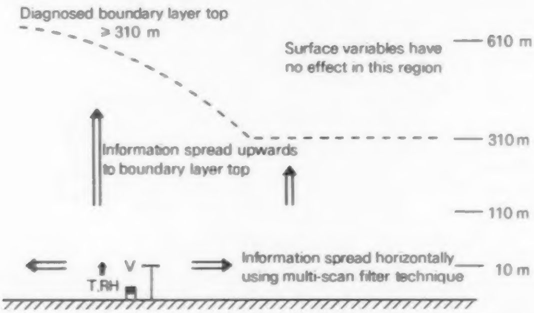

Figure 8. Schematic diagram of the method of incorporating surface observations into the model initialization. T—Temperature, RH—relative humidity and V—wind velocity.

boundary layer is present in the atmosphere, it can be assumed that information about the surface quickly reaches the boundary layer top. The corrections at 10 m are therefore applied with decreasing weight at higher levels up to a diagnosed boundary layer top. This is defined as the level at which parcels from 10 m, rising with a slightly positive lapse of potential temperature, will cease to be buoyant, provided it is at or above the third model level.

The use of cloud observations is illustrated in Fig. 9 and has been described in Higgins and Wardle (1983). Surface observations are used to correct the values of cloud base, cloud top and precipitation rate which are all diagnosed from the regional model. The model's precipitation scheme is then used to define the cloud water mixing ratio which, with the analysed cloud depth, will give the analysed rainfall rate. At the 10 m level, fog observations are also used to correct the cloud water values.

Some comparison runs have indicated that the forecast is quite sensitive to the enhancement of initial conditions described above and, in particular, to the cloud data.

4. Examples

A version of the model containing all the processes described here was first produced in October 1983. During late 1983 a number of case studies were run which indicated where further work was needed but also showed sufficient skill to justify starting a weekly trial of the model from the start of 1984. Since then several good forecasts have been obtained although weaknesses remain at present.

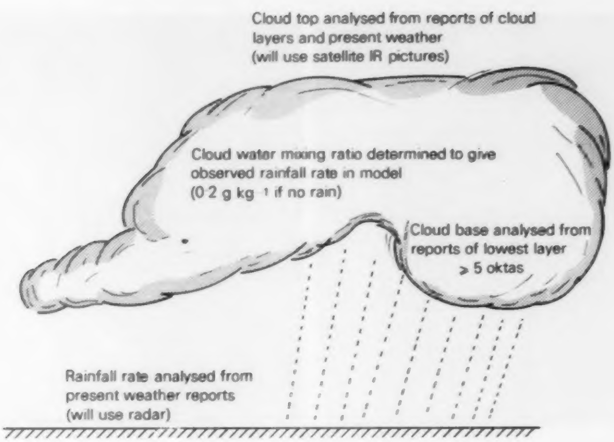

Figure 9. Schematic diagram of the method of incorporating cloud observations into the model initialization.

An example of a forecast from the model is shown in Fig. 10 with a verification chart in Fig. 11. The information displayed was extracted from charts of several model variables but could, in principle, be obtained automatically. It shows a 6-hour forecast from a data time of 06 GMT on 12 December 1983. An occlusion was moving slowly eastwards with a belt of associated rain and snow and was followed by a cold airstream with showers, especially on coasts. In the observations (Fig. 11) the 1 °C surface isotherm was a good indicator of the boundary between rain and snow. Although somewhat larger in area in Fig. 10, the prediction of snow using this indicator would have given excellent guidance to a forecaster. The timing is not quite correct with the frontal rain belt a little slow and too small a gap behind it before the showers start. However, it is encouraging to see the model prediction of a cluster of showers in the Midlands, close to the reported snow. It should be noted here that the model will naturally appear to have a greater density of showers than observed because its resolution is finer than the reporting network. Nevertheless, the predicted showers on the north-east coast are clearly erroneous. In the north-west the model has predicted a lot of convective cloud but mainly light rain from stratiform cloud rather than showers. This is because the convection scheme did not account for the effect of the freezing level on shower precipitation and finds insufficient water in the clouds to produce rain. The result is a thick deck of stratocumulus cloud giving drizzle. A simple change to the convection scheme has been made to correct this behaviour.

During February and March 1984 an extended period of anticyclonic weather affected England with spells of cold north-easterly winds and overcast skies. A number of forecasts were run in this period and they demonstrate the skill of the model in forecasting surface temperature when air mass changes are not occurring. Fig. 12 shows the surface temperature curve for Heathrow from the model compared with that observed on 27 February 1984. A thick layer of low stratus persisted throughout the day and although the model cloud was not quite thick enough, the temperatures show very good agreement. In contrast to this case, Fig. 13 shows a comparison for the same location on the following Saturday when the cloud was well broken. The agreement is again quite good, the main error being the excessive fall of temperature in the first hour. These cases show that the model can correctly represent the effects of the presence or absence of low cloud on the surface temperature.

Plate I. The FRONTIERS work station with an operator at work.

Plate II. Radar network picture derived automatically from radars 1–4 in Fig. 1. Colours represent equivalent rainfall intensity at intervals of a factor of two starting with light blue for rates up to 1 mm h^{-1}. Yellow circles represent maximum radar ranges of 210 km. The white line has been drawn by the operator to demarcate areas of spurious echoes due to interference.

Plate III. Cleaned-up radar network picture with spurious echoes deleted. Colour key same as Plate II.

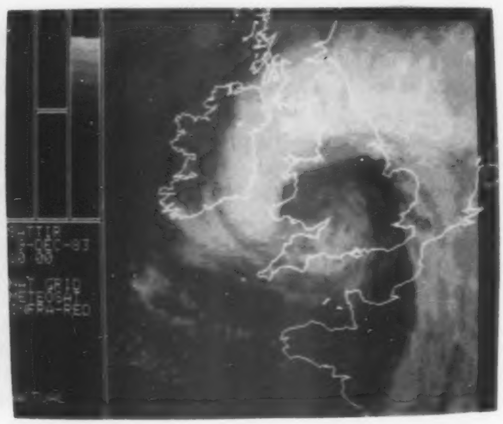

Plate IV. Infra-red Meteosat cloud picture. The brightest areas represent the coldest cloud tops.

Plate V. Combined radar and Meteosat picture. Meteosat data above a certain threshold are used outside the area of good radar coverage and show as mainly light blue. The white line has been drawn by the operator to demarcate areas where rain was probably not reaching the ground.

Plate VI. Same as Plate V but with resolution reduced from 5 to 20 km and the light blue area beyond the white line deleted.

Plate VII. Same pattern as Plate VI but with the colours now denoting different rainfall clusters. The velocities of the clusters are shown by yellow vectors.

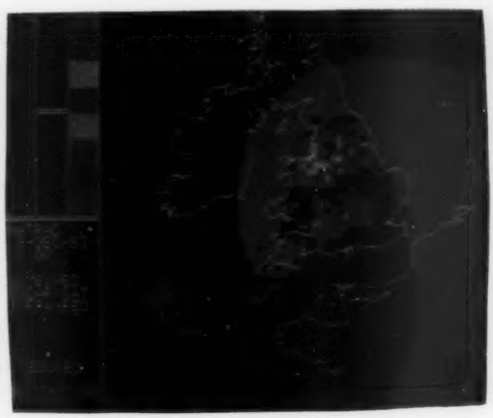

Plate VIII. Extrapolation rainfall forecast for $T + 2$ hours, in the same format as Plate VI.

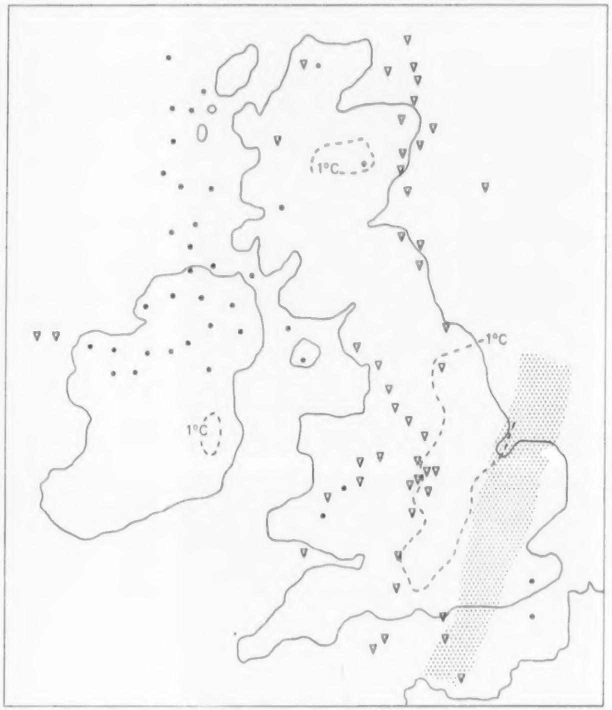

Figure 10. Six-hour model prediction of the weather for 12 GMT on 12 December 1983. Triangles indicate showers, and dots are very light layer cloud precipitation. The shaded area in the south-east is the main layer cloud precipitation belt and the dashed lines enclose areas below 1°C where snow is predicted.

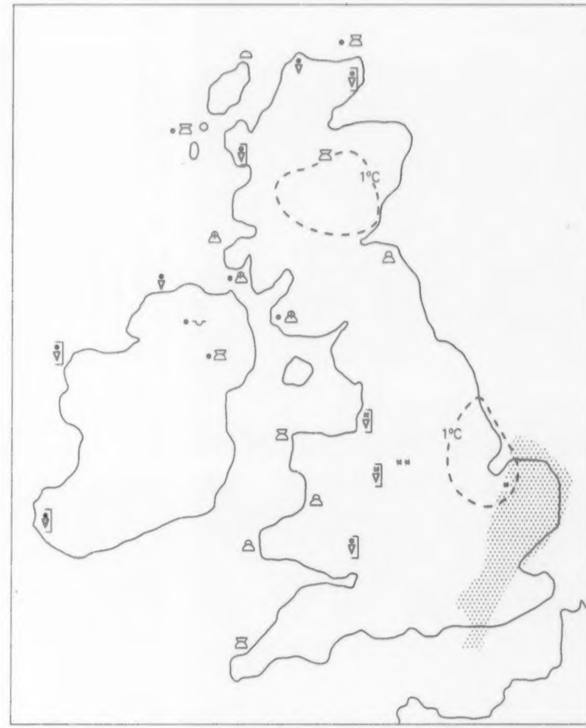

Figure 11. Observations at 12 GMT on 12 December 1983. Cloud and weather symbols indicate the extent of showery activity (for meanings see World Meteorological Organization 1974 and 1977). The shaded area in the south-east is the main frontal precipitation belt and the dashed lines enclose areas below 1°C where snow was reported.

During the tests some faults in the model have been identified. These are mainly associated with the boundaries which are of particular importance because of their proximity to the forecast area. Work is in hand to correct these faults. A more difficult challenge is posed by the sensitivity of the model to its initial conditions, especially cloud. A great deal of work remains to be done to incorporate all the available information from radar, satellite pictures and radiosonde ascents as well as from the surface reports. As the use of these data increases, the model forecasts can be expected to improve further.

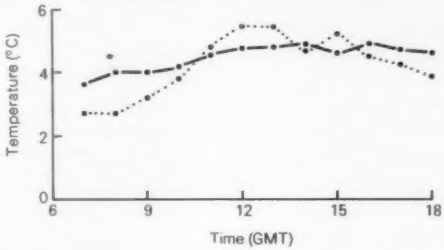

Figure 12. Comparison of 12-hour model-predicted (dotted line) and observed (solid line) temperatures for Heathrow starting at 06 GMT on 27 February 1984.

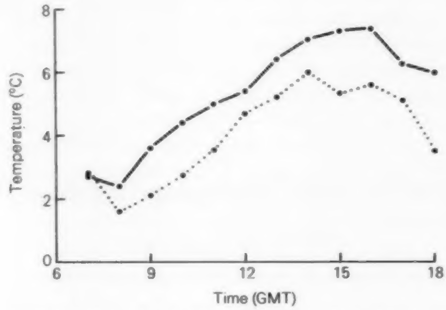

Figure 13. Comparison of 12-hour model-predicted (dotted line) and observed (solid line) temperatures for Heathrow starting at 06 GMT on 3 March 1984.

5. Conclusions

A short-range, fine-scale forecast model has been developed for forecasting for the British Isles. Many of the physical parametrizations have been specially written to take account of the scales represented by the model. A sophisticated scheme for analysis of surface synoptic reports has been developed for preparing fine-scale initial data of the boundary layer and cloud fields. The complete system has been under regular test since the beginning of 1984 and has produced some encouraging results. However, further development and testing are required before it can be used for operational guidance. In particular the format in which the output will be presented to forecasters must be determined. This is a much more complicated task for a model that predicts variables such as cloud, rain and visibility than for one whose main prediction is a pressure pattern. In addition, facilities must be developed for checking the forecast and making any necessary modifications. On the broad scale this may be done centrally but detailed processing for specific requirements will have to be done at the outstation where the guidance is used. The techniques which might be used in these processes form the subject of a paper by Browning and Golding (1984).

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Mesoscale forecasting in the Meteorological Office: the way ahead?

By K. A. Browning

(Meteorological Office Radar Research Laboratory, Royal Signals and Radar Establishment, Malvern)

and B. W. Golding

(Meteorological Office, Bracknell)

Summary

Two companion papers in this issue have discussed the sort of mesoscale products that will become available if FRONTIERS and the mesoscale model are implemented operationally in the Meteorological Office Central Forecasting Office. This paper considers some of the challenges that will be encountered in exploiting the new forms of guidance and an attempt is made to deal with them from the viewpoint of an outstation forecaster. The paper looks ahead to the early 1990s when advanced interactive display systems are likely to be sufficiently inexpensive to be used at major outstations.

1. Introduction

Meteorologists are justifiably proud of the improvements in forecasting skill for periods of more than 24 hours ahead that have been achieved by advances in numerical weather prediction. These advances have, however, had little influence on forecasts for shorter periods. It has to be said that guidance issued centrally is still lacking in local detail, whilst at the outstations, where most of the short-period forecasts are issued, the mode of working is still, in many respects, much as it was 30 years ago. There is, moreover,

little prospect of improvement by conventional means. Although there have been some small advances, brought about by recent research, in conceptual understanding of the behaviour of the atmosphere on the mesoscale, the scarcity of data from existing, conventional observing networks does not allow these to be used effectively for local forecasting.

As suggested in a recent review (Browning 1980), however, we believe we are at the threshold of a new era in local forecasting. Two important ingredients for improvement lie in the advances in the use of satellite and radar for observing on the mesoscale (e.g. Browning and Carpenter 1984) and in the development of mesoscale numerical weather prediction methods (Golding 1984). A further ingredient is the revolution in information technology and telecommunications; this not only forms the basis of the first two ingredients but will also enable the resulting forecast products to be disseminated to users in a rapid and cost-effective way. The challenge will be to blend these ingredients into a working system — one that can cope with the generation, quality control and rapid distribution of the large variety of tailor-made forecast products that the new forecast methods will be capable of delivering. The manner in which the new local forecasting methods might be implemented within the context of the Meteorological Office and the role of the forecaster are the subjects of this paper.

The implementation of a total system depends to a great extent upon the design of the telecommunications network. To this end a strategy for the Meteorological Office has recently been agreed whereby all forms of data and forecast guidance will be sent in digital form via fast links (64 kilobits per second) to outstations. Local storage and processing power will enable separate data streams to be manipulated and displayed according to local requirements. Initially, at the outstations, alpha-numeric data will be presented on displays known as ROASTs (Remote Outstation Automation System Terminals), imagery on colour monitors known as Jasmin displays, and numerical model products on digital facsimile outlets. These are all separate displays and, whilst the outstation forecasters will doubtless wish to retain the facility of continuously available separate displays, we shall be stressing in this paper the need to evolve towards a system in which he will, in addition, be able to combine and compare different products on a common display. The interactive display and manipulation of the combined data sets at an outstation are discussed in section 4. Similar interactive methods are important also for the centralized generation of the new mesoscale products, as discussed in section 3 (see Browning and Carpenter 1984). First, however, in section 2, we make some more general points.

2. General considerations

2.1 *Analysing on the mesoscale*

A primary requirement in local forecasting is to identify mesoscale features of the weather having significant variability on scales of tens of kilometres and over periods of an hour or so. The network of conventional (*in situ*) observations by itself is not capable of resolving this variability. On the other hand, imagery from the geostationary satellite Meteosat and from the growing network of weather radars provides fields, with the necessary resolution in both space and time, of several important weather elements: precipitation intensity, cloud extent and cloud-top temperature, and, in cloud-free areas, land and sea surface temperatures. These fields can help the forecaster make more sense of the relatively sparse network of conventional observations, and thus aid him in the preparation of finer-scale analyses of more elusive elements such as visibility. We have already caught a glimpse of the operational value of satellites and radar but at most outstations the only experience of these data is as pieces of paper separate from the main charts. In one or two forecast offices the same data have begun to be presented as moving images on a television screen. This is certainly helpful but it represents only the tip of the iceberg of opportunity.

2.2 *Forecasting on the mesoscale*

Two basic approaches are being developed in the Meteorological Office to enable centralized generation of mesoscale forecast guidance:

(i) Extrapolation or advection of detailed observed weather patterns — the nowcasting approach.

(ii) Prediction using a mesoscale numerical model — the dynamical approach.

The Meteorological Office effort in nowcasting, which goes under the name of FRONTIERS (Browning and Carpenter 1984), is at present focusing on the use of radar and satellite data for monitoring and forecasting precipitation. Another system being developed, known as HERMES (High-resolution Evaluation of Radiances from Meteorological Satellites), is providing soundings of high spatial resolution using the TIROS-N Operational Vertical Sounder (TOVS) data from the NOAA satellites (Eyre and Jerrett 1982). The HERMES system is also being used to develop techniques for deriving high-resolution products from AVHRR (Advanced Very High Resolution Radiometer) imagery, such as fog and cloud-type analyses as well as surface temperatures. The dynamical approach, which is under development in the Meteorological Office Forecasting Research Branch (Golding 1984), lends itself to forecasting a wider range of elements. The output of both forecasting methods can be refined for particular applications either by subjective interpretation or the use of statistical methods (e.g. model output statistics).

The basis of the nowcasting approach is for the evolution of meteorological fields to be monitored closely and for the future state to be derived by assuming the current patterns will continue to move in the same way essentially without development or decay. Very detailed site-specific forecasts can be derived using this approach but their accuracy falls off rapidly with forecast period. The use of the term nowcasting underlines the heavy dependence on the description of the current situation.

The dynamical method uses a primitive equation model with a horizontal grid length of about 10 km which is initialized using a combination of forecast fields from a model of lower resolution and recent observational detail from a variety of sources. These inputs are reconciled by means of a process of near-continuous assimilation. The resulting mesoscale forecasts have the great advantage that they take into account development and decay. Compared with the nowcasts, however, they suffer from being based on less recent data and also from a degradation in spatial resolution. The smallest scale that can be properly represented is about 40 km except perhaps when topography exerts a strong influence.

The products generated by the nowcasting approach can be expected to be superior for forecast periods of, for example, zero to four hours, because they are better able to represent the actual fine-scale variability (which in the case of precipitation can be very great). For longer periods development and decay become important and the products of the dynamical approach should then become superior. Thus it is not a question of either the dynamical or the nowcasting method being superior to the other — they are complementary. The break-even point of four hours, mentioned above, is not well defined: we might expect it to be as much as six hours in some frontal situations, for example, but less than two hours in situations of rapidly evolving thunderstorms especially where topography has an important effect. Thus one of the tasks when generating a local forecast for a few hours ahead will be to choose between or reconcile the guidance produced by these two methods. It is important, therefore, for the forecaster to be provided with the necessary facilities to be able to display, compare and combine these two sets of central guidance.

2.3 *The work station concept*

The need for the forecaster to combine or compare multiple data sets, including their evolution, arises in a number of contexts. One will arise centrally where conventional, satellite and radar data need to be analysed together (i) to produce the nowcasts and (ii) to initialize the mesoscale model. The other, just

discussed, is where a forecaster needs to reconcile the two sets of central guidance that have been derived in different ways in order to prepare user-specific forecasts.

There is thus a general need to combine diverse data sets. Large sets of data have to be manipulated and this has to be done very rapidly under the control of forecasters. It is our view that this should be achieved using digital data sets displayed on interactive video displays — so-called work stations. The common element in the design of all meteorological work stations is that they should enable the data streams to be combined, action replayed and amended on a common scale and map projection. By means of modern man–machine interface techniques the forecaster can analyse the merged products, operating directly on the data base, using a light-pen or his finger on a touch-sensitive television screen much as he would a pencil or rubber on a plotted chart.

It will be possible, given an appropriate local processor, to implement various automatic procedures for the more routine tasks, e.g. objective analysis and extrapolation. However, the incomplete nature of the data sets is such that the forecaster is almost always likely to be in the position of needing to refine the products subjectively in important areas. In doing so he might be aided by computer-archived climatological statistics or diagnostic packages, but his selection of the appropriate supporting information will depend on his understanding of the physical/dynamical mechanisms at work in the atmosphere as well as on the particular demand he has to satisfy.

The idea behind the work station, in a nutshell, is to simplify the routine chores of basic data manipulation so that the forecaster is given maximum opportunity to exercise his judgement within the context of what is otherwise a highly automated system. It provides the forecaster with the tools so that he can respond to the customer's requirements with the maximum effectiveness which the science and technology will allow.

2.4 *Machine-assisted tailoring*

A weakness of the present outstation forecasting system is that the forecaster has to spend too much time carrying out the routine aspects of the work needed to tailor the products to the formats required by the customer. An advantage of the work station approach is that, by having all the working data in digital form, the analyses and forecasts that the forecaster generates on the monitor screen are ready to be tailored and disseminated automatically. Part of the continuing role of the forecaster will be to provide the appropriate emphasis for the user and an indication of confidence in the product. In some circumstances products can be provided direct to the user in predetermined formats. Given sets of hourly forecast fields derived using the work station, it would, for example, be possible for 'point' forecast sequences to be generated and disseminated automatically for an array of small sub-areas within the whole forecast domain. It would also be possible for forecasts for non-standard locations, or along flight tracks, to be generated automatically in response to the forecaster pointing to the appropriate locations on the monitor screen.

2.5 *Modern dissemination methods*

Very-short-range forecasts are by their very nature highly perishable: they must be disseminated promptly if they are not to lose their value. Advances in information technology and particularly in telecommunications now offer the means for rapid dissemination and also new methods for presenting the material conveniently to the user. In some cases dissemination may be by direct computer-to-computer link to the data user's control system. In many cases, however, the user will find it convenient to have a visual presentation of the information. One approach is to use high-speed dedicated lines to colour-monitors and other displays at outstations as mentioned in the Introduction. Another approach, appropriate to customers requiring only intermittent access to specific information, would be to use a viewdata system. The British Telecom viewdata system, Prestel, suffers in its basic form from

poor resolution and the requirement for a specially modified television set. However, with one of the telesoftware schemes now available, a user may, by making a local telephone call to the Prestel data base, receive and display on an unmodified domestic television set both textual and pictorial data having good resolution. To do this, all he needs is a low cost modem and a personal microcomputer of a kind now commonplace in homes and offices.

It is clear that information technology is opening up all sorts of creative marketing opportunities — opportunities for adding value and for aiming the product at different market sectors. Access to different parts of the data base would be controlled through a system of 'closed user groups'. Each time a page of information is accessed a charge would be automatically levied by the information provider. The automatic tally of the usage of different pages could be stored in the management and accounting information system and would be readily available for market research. Market research will become more important with the availability of increasingly flexible methods of deriving and delivering tailored products.

3. New mesoscale facilities within the context of the Meteorological Office Central Forecasting Office (CFO)

3.1 *Overview*

In CFO at present two numerical models provide guidance to the forecaster — the fine-mesh and coarse-mesh models. Neither of these is capable of representing mesoscale phenomena, although the fine-mesh model is an improvement over earlier models in its ability to predict synoptic-scale features. During the next few years mesoscale products may become available from the mesoscale model, FRONTIERS, and HERMES-type facilities so as to extend the central guidance on the mesoscale. The central forecasting facilities would then be as shown in Fig. 1. When these new facilities are fully

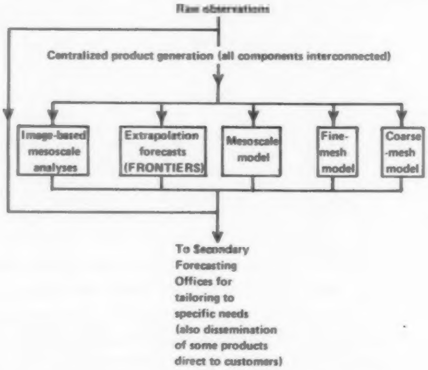

Figure 1. Central Forecasting Office facilities.

operational CFO will be capable of generating an impressive range of guidance, covering a variety of weather elements over a wide range of scales as summarized in Table I. The main preoccupation of CFO will, however, continue to be with large-scale phenomena and, although a limited number of mesoscale products may be disseminated directly to end-users, the mesoscale guidance is likely to be used mostly by

Table I. *List of products capable of being generated centrally*

		Nowcast products			Dynamical products		
		HERMES-type analyses		FRONTIERS analyses and extrapolation forecasts using Meteosat and radars†	Mesoscale model†	Fine-mesh model	Coarse-mesh model
		from NOAA TOVS†	from NOAA AVHRR†				
Parameters		temperature humidity	cloud fog* surface temperature	precipitation cloud	temperature wind cloud precipitation	pressure wind temperature precipitation	pressure wind temperature
Spatial resolution (km)	analyses	75 or better	1	5	10	75	150
	forecasts	–	–	20	30	75	150
Area of coverage		N Atlantic and Europe	British Isles	British Isles	British Isles	N Atlantic and Europe	global
Period of forecasts (hours)		–	–	1–6	3–18	6–36	12–144
Interval of forecasts (hours)‡		–	–	1	1	6	12
Availability after data time (hours)	analyses	$T+1$	$T+1$?	$T+\frac{1}{3}$*	$T+1$	–	–
	forecasts	–	–	$T+\frac{2}{3}$	$T+2\frac{1}{2}$	$T+3\frac{1}{2}$	$T+6$
Interval (hours) between issue of new products	analyses	6	6	½*	1	–	–
	forecasts	–	–	½	6	12	12

*Less for raw radar composite data
† The mesoscale components of the forecasting system
‡ i.e. interval between validity times of successive members of a series of forecasts made from the same data

the network of Secondary Forecast Offices (SFOs) to which it is distributed. The SFOs may have regional responsibilities, as at Weather Centres, or they may serve specialized interests such as at RAF airfields; however, in this paper we shall use the term SFO for generality. The main role of the SFOs is to refine and tailor the central guidance for specific customers.

Internally, within CFO, the various components shown in Fig. 1 will need to interact with one another. Thus the coarse-mesh model supplies boundary conditions for the fine-mesh model, and the fine-mesh model for the mesoscale model. The mesoscale model in turn will help in the derivation of extrapolation forecasts obtained by FRONTIERS, whilst products from FRONTIERS and HERMES will help in the initialization and updating of the mesoscale model. Sounding products from HERMES will probably be used both to initialize the fine-mesh model and to help in the interactive analysis for the mesoscale model as discussed later. All this calls for an advanced local communications network at Bracknell and multiple facilities for man–computer interaction within CFO so that forecasters can exercise judgement concerning the manner and extent to which each of these products is permitted to influence the other. The nature of the forecaster's interaction varies from the limited subjective quality control and 'bogusing' of observations currently practised for the coarse- and fine-mesh models to a very high degree of interactive analysis as required for FRONTIERS and for the mesoscale model.

3.2 *FRONTIERS nowcasting facilities within CFO*

Details of the FRONTIERS system are given by Browning and Carpenter (1984). In brief it is an interactive system by means of which a forecaster can blend data from a network of weather radars and Meteosat, in the light of other information, so as to generate frequent analyses and forecasts of the precipitation distribution. FRONTIERS is being developed for use as a central facility so that forecasters expert in radar and satellite meteorology can come to grips with the unusual error characteristics of radar and satellite data. The intention is that a forecaster at a SFO using guidance produced by FRONTIERS would not have to worry unduly about the peculiarities of the observing techniques but would instead receive quality-controlled analyses and forecasts of precipitation.

The main characteristics of the FRONTIERS guidance are summarized as part of Table I. A precipitation actual plus a set of forecasts could be generated every half-hour and distributed as images for display on a colour monitor according to the schedule given in Table II.

Table II. *Half-hourly interactive cycle for FRONTIERS*

Minutes past each half-hour	
0	Data time
<10	Precipitation data received from network of radars
10–20	Analysis and quality control of radar data
20	Possible dissemination of quality-controlled precipitation actual
20	Meteosat imagery received
20–30	Meteosat imagery interpreted in terms of precipitation by a combination of objective and subjective analyses and then combined with radar data to extend coverage
30–40	Extrapolation forecasts generated by a combination of objective and subjective methods
40	Dissemination of precipitation (and cloud) forecasts

In addition to this half-hour cycle, radar composites may continue to be available at 15-minute intervals, within about 5 minutes of data time but without the benefit of FRONTIERS quality control.

The data from radar and Meteosat are particularly well suited to very-short-range forecasting because of their frequency: every half-hour or better. Data from polar-orbiting NOAA satellites are available at only six-hour intervals (assuming two satellites) but nevertheless they are useful for mesoscale forecasting because of their ability to produce very high spatial resolution imagery for identification of cloud type and fog (from AVHRR imagery) and mesoscale resolution soundings (from TOVS).

3.3 *The mesoscale model within CFO*

Details of the structure of the model are given in Golding (1984). It is planned that the model shall cover mainland Britain and Ireland using a grid length of 10 km. With the model covering such a small area, the effects of boundary conditions will quickly become important. The forecasts will, therefore, be restricted to periods of up to about 18 hours and will have to be repeated at frequent intervals. A satisfactory arrangement may be four model runs per day. The timing of such runs will depend partly on the user requirements. It is also necessary to devise a cycle which fits into the cycle of other operational forecasts and at the same time benefits from up-to-date inputs from the fine-mesh model. A possible schedule is shown in Table III, according to which, mesoscale model guidance would reach SFOs at about 0230 GMT, and again at 0830, 1430, and 2030 GMT.

An essential part of the mesoscale model operational cycle in Table III is the hourly interactive analysis, each analysis being followed by a one-hour model forecast to provide a first guess for the next hourly interactive analysis etc. A forecaster working with the computer through a graphics display will produce analyses for the whole of the British Isles for a wide range of variables using mainly surface observations together with radar and satellite images from FRONTIERS and the HERMES soundings.

Table III. *Six-hour operational schedule for mesoscale model*

Time (GMT)	
0000	
0030	Interactive analysis of 0000 data
0100	Run forecast from 0000 to 1800
0130	Interactive analysis of 0100 data
0200	Check forecast results, 0000 to 1800, and start dissemination
0230	Interactive analysis of 0200 data
0300	
0330	Interactive analysis of 0300 data
0400	
0430	Interactive analysis of 0400 data
0500	
0530	Interactive analysis of 0500 data

The analysed variables will include surface pressure, temperature, humidity and wind; precipitation intensity; layer and convective cloud amounts, bases and tops; and visibility. In short, the end product of each interactive analysis will be a detailed picture of the weather over the whole country. Objective analysis schemes will be employed but the forecaster should be able to exploit his judgement, e.g. to incorporate discontinuities in mesoscale fields inferred from radar and satellite imagery. Although carried out for the purpose of initializing the mesoscale model, these interactive analyses will be a valuable input in their own right to the work of the Senior Forecaster in CFO and will be a natural development of the advice currently given to him by the British Isles Forecaster in CFO.

In the hourly schedule in Table III only half an hour has been allocated to the task of interactive analysis. Clearly, therefore, the interactive dialogue will have to be developed carefully so that the forecaster can contribute as much as possible in that time. This development will be undertaken on a powerful interactive graphics system which is being acquired in 1985. One can expect that the steps involved in the interactive procedure will resemble those in Table IV. For each step the computer will highlight the areas that need attention, e.g. by comparing observations with first-guess fields to show up suspect reports, or comparing analyses against observations to show where the analysis has failed to fit the observations.

The interactive analyses, in addition to providing the initialization for the forecasts, would provide a check on the last forecast issued. If substantial deviations are noted, the fields might be updated and the resulting revised forecasts disseminated again. In such circumstances, the forecaster would have little time to make detailed amendments and might simply have to blank out parts of a field. At some times of the day it might be possible to rerun the numerical forecast if the error became sufficiently serious.

The mesoscale model output will initially be used in CFO as additional guidance in the preparation of regional forecasts for the Synoptic Review*. The full usefulness of this guidance will not be realized,

*A review of the expected weather for the United Kingdom, and the associated synoptic development

Table IV. *Hourly interactive analysis cycle for mesoscale model*

Minutes past each hour		
00–20	Observations received; computer forecasts first guess for analysis using analysis for previous hour	
20–50	Interactive analysis:	(a) Quality control observations (b) Objective analysis (c) Modify objective analyses by comparison with station observations, imagery and other analyses (d) Objective transformation to model variables (e) Selective checking of model fields near key observations especially where imagery implies discontinuities or soundings give vertical structure
50–60	Dissemination of analyses, warnings, etc.	

however, until it is available at SFOs where the information can be refined and tailored to the needs of the customers. In principle, the model is capable of forecasting a wide range of variables including, as already noted, visibility, wind, temperature, rain, height and type of cloud layers, and also turbulence. The vertical resolution is such that information on temperature, wind and moisture could, for example, be presented at five levels below 1 km. This amounts to a lot of data and it will be important, therefore, to consider the form in which these products might be made available to the SFOs. The quantity of data distributed may be reduced by degrading the resolution. Although the full resolution of the analyses will be useful, much of the detail at individual grid points of a forecast will be spurious. Thus the forecast resolution can probably be degraded to about 30 km without loss of significant detail.

4. New mesoscale facilities required within Secondary Forecasting Offices

4.1 *Nature of the requirement*

The task of the outstation forecaster at a SFO is to take the centrally-generated guidance and use it selectively to provide forecast products for specific areas, variables and applications. This involves him in three categories of activity:

(i) *Selecting* the products appropriate to his needs (thus, for example, for some applications he may choose to use the FRONTIERS rainfall forecast for 2 hours ahead without modification, whilst for another application he may use the mesoscale model forecast of temperature 12 hours ahead without further analysis).

(ii) *Modifying* aspects of the central guidance to provide an improved product for a specific requirement (thus, for example, if he requires a forecast of cloud base for two hours ahead, he may need to carry out a combined analysis reconciling the FRONTIERS product, mesoscale model products and certain surface station observations in the light of information about the local climatology).

(iii) *Tailoring* the wanted information in a format to suit the needs of the customers.

In order to facilitate performance of these tasks, new kinds of facilities are needed in the SFO. They are best regarded as a development of the Outstation Automation System (OASYS) already implemented in three offices. Both hard copy and soft copy outputs are provided by OASYS; what we believe is needed is an extension of the soft copy component. In the present OASYS system the VDU is essentially an efficient filing system enabling easy selection, display, and also action replay. The required system, in our view, will need to be a fully interactive work station of the kind discussed in section 2.3, supported by a local host computer and capable of providing facilities for combining different forms of

data and for analysing them on the screen. Some experience in work station design has already been gained within the Meteorological Office with the FRONTIERS interactive display (Browning and Carpenter 1984); however, that system is narrowly focused on the nowcasting of precipitation, and so it depends mainly on radar and satellite data and only marginally on other kinds of data. The required work station system for the SFO has to be suited to a wider range of forecasting responsibilities. Similar weight has to be given to station observations, to computer-derived fields from fine-mesh and mesoscale models, and to radar and satellite data.

4.2 *A work station configuration for use at a Secondary Forecasting Office*

A possible work station configuration is shown in Fig. 2. It consists of (a) a data display panel, with three intelligent displays, and (b) an interactive analysis display. The data display panel is just a filing system with rapid access and easy viewing facilities. It enables the forecaster to have simultaneous full-size displays of selected FRONTIERS or HERMES-type products, the mesoscale or fine-mesh model

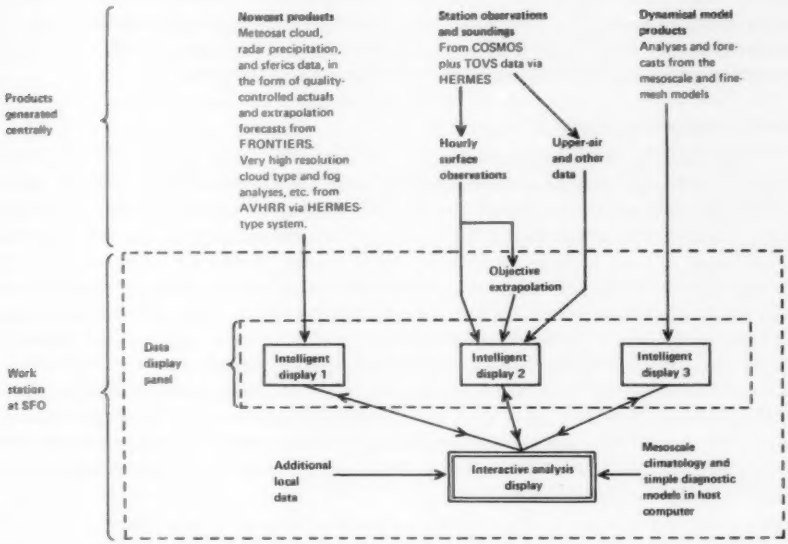

Figure 2. Secondary Forecasting Office (SFO) facilities.

products, and basic station observations, thereby enabling him to achieve a time-lapse replay of any of these whilst continuing to view the others undisturbed on the adjacent displays. The interactive analysis display enables the forecaster to combine products from the other three displays and to amend them for his purposes (whilst retaining the capability of referring to other products on the data display panel without disturbing his working display). Although the work station shown in Fig. 2 is essentially a soft copy system designed for easy manipulation of the data, limited facilities for providing hard copy will also be needed for some briefing purposes.

(a) *The data display panel*

The FRONTIERS and conventional products on displays 1 and 2 (in Fig. 2) would be available promptly within half an hour or so of data time. The mesoscale and other model products on display 3, however, would be based on older observations. Thus the outstation forecaster interested in the period about two hours ahead, say, would often be concerned to reconcile the nowcast and observational data on displays 1 and 2 with the information on display 3 which, though less up-to-date and detailed, nevertheless would have benefited from a dynamical treatment.

Each of the three displays in the data display panel would, according to our scenario, hold a sequence of charts including several actuals and hourly forecasts. In the case of displays 1 and 3 the forecasts would be based on those generated at CFO; however, for display 2 it is possible that the forecasts for certain surface variables might be derived at the outstation itself for the particular area of interest using simple objective analysis and extrapolation algorithms, and supplementing the observations from CFO with more frequent (15-minute) observations received direct from local stations. It would thus be possible to show, on display 2, sequences of actuals plus simple extrapolation forecasts for such variables as temperature, dew-point temperature, dew-point depression, pressure, gradient wind, pressure tendency, wind speed and direction, divergence, cloud base and amount, and visibility. These elements could be displayed one at a time if desired. The station observations (alpha-numerics) and fields (colours or lines) of a given element could be viewed either separately or together.

(b) *The interactive analysis display*

The set of three intelligent displays constituting the data display panel would be for monitoring purposes only and, although the outstation forecaster could interact with the system in the limited sense of selecting different frames and replays, he could not intervene directly to modify any of the fields being displayed there. To do this he would instead use the large interactive analysis display (Fig. 2). This single monitor would need to have a large number of image planes, preferably with separate brightness controls, so that any required combination of the actuals and/or extrapolation forecasts could be superimposed at any brightness level — rather like stacking charts on a light table. To select images for display and manipulation on the interactive analysis display the forecaster could simply transfer whatever frame he had called up for display on the data display panel.

Having transferred products from the data display panel to the interactive analysis display, the outstation forecaster would first compare them to establish their consistency. He might then modify the automatically-derived fields (i.e. redraw isopleths) so as to carry out the following kinds of tasks:

(i) Removing any obvious errors in the objective analysis (such as those sometimes associated with closed contours around single station reports).

(ii) Refining computer-derived fields, interactively where necessary (e.g. detailed rain and cloud patterns from radar and satellite imagery will enable the analyses of other parameters to be refined near fronts and other mesoscale features).

(iii) Adjusting for expected errors in the extrapolation forecast products as indicated by numerical model guidance or as inferred from the nowcast data themselves (e.g. the predicted arrival of a wind shift will alter the influence of local topography on cloud base etc.).

In carrying out these tasks the forecaster could be aided by mesoscale climatological information, topography overlays, etc., stored in the host computer. He could also use this computer to insert local data and to run simple diagnostic models and evaluate empirical formulae corresponding to local forecasting rules of thumb. In addition it would be helpful for him to be able to access a variety of derived products from the synoptic data base such as cross-section analyses along arbitrary sections. Finally, having carried out an interactive analysis of the kind just described, the forecaster could transfer his re-analysed chart back to the appropriate monitor on the data display panel where it would be ready

for automated tailoring and dissemination according to predetermined procedures. Although the forecaster in a SFO would be concentrating his attention on refining the forecasts for specific areas and purposes, many of the tools enumerated above are similar to those needed by a mesoscale analyst in CFO; obviously these procedures must be developed in harmony.

5. Concluding remarks

What are the main problems in establishing and exploiting a system of the kind outlined in this paper? One problem is that of clarifying user needs and developing new markets. This takes on added significance with the new opportunities for greater specificity in the forecasts. Another, which will be with us into the next century, is that of obtaining better mesoscale observational inputs to the system. The challenge of extending numerical modelling down to smaller scales and to periods less than 12 hours ahead is being tackled by the current efforts with the mesoscale model. A telecommunications strategy has been agreed that will enable the required amounts of digital information to reach the outstations rapidly; however, an important bottleneck, highlighted in this paper, is the forecaster's difficult task, both centrally and in the outstations, of integrating and analysing the large data sets that already exist and which are likely to become more widely available and more extensive soon. Programs therefore should be set up in which forecasters, research meteorologists and systems designers can work together to develop and test work station practices for mesoscale analysis and very-short-range forecasting. An aspect of such programs will be to investigate the division of effort between CFO and outstations. Some tasks requiring a high degree of precision and specificity will require close customer contact and a high level of subjective interpretation to get the most out of the available guidance. Such tasks may be more appropriately undertaken at outstations. On the other hand, checking the consistency of the synoptic-scale development in different forecast products may be better done centrally.

Although an early task has to be the establishment of prototype work station facilities, a more challenging task will be that of learning how best to use them: only practical experience with using the merged data sets will tell us how to optimize the forecasting procedures. There will be a continuing need for the outstation forecaster in particular to interpret the guidance subjectively in the light of conceptual models of atmospheric behaviour. However, conceptual models now in use still owe too much to the early frontal models of the Norwegian School. Thus there is a continuing requirement to learn more about the structure, evolution and mechanism of mesoscale and synoptic-scale weather systems and their interdependence. In the long run, improvements in mesoscale forecasting are likely to be limited by meteorological understanding and our ability to interpret new forms of observational data.

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Reviews

Mesoscale meteorology — Theories, observations and models, edited by Douglas K. Lilly and Tzvi Gal-Chen. 160 mm × 245 mm, pp. x + 781, *illus.* D. Reidel Publishing Company, Dordrecht, Boston, Lancaster, 1983. Price Dfl. 220, US $88.00.

This substantial book on mesoscale meteorology forms the Proceedings of the NATO Advanced Study Institute on Mesoscale Meteorology — Theories, Observations and Models, held at Bonas, France in 1982. It comes at a time when several new books on mesoscale meteorology are appearing. In many ways it is a compromise between a conference proceedings consisting of separate papers, and an advanced textbook. The order of the original lectures has been modified by the editors in an attempt to impose a structure to the volume. Unfortunately this has not been very successful and in some places has destroyed the coherence that papers on different subjects by the same author have. As a textbook, one feels that it would have benefited if about half the papers had been left out. On the other hand some of the reviews are excessively long for the proceedings of a conference.

There are eight sections, the first of which is an introduction on scales of motion, the next six are ordered by decreasing scale, and the last is on observational technology. The attempts to 'define' mesoscale in section 1 seem to be judged by their lack of use in the rest of the book. The second section on cyclonic scale motions and prediction models is a collection of almost unrelated papers. The main one is by Buzzi and Speranza on lee cyclogenesis and contains much interesting material. Unfortunately a few of the diagrams have not reproduced well. There is no summary or conclusion so the reader has to go through all 88 pages. Two papers on initializing mesoscale models only touch the surface of the problem and could have been omitted without much loss. The third section is on fronts and has a valuable historical introduction by Sanders. However, I was disappointed to find no references in this section to the work on frontal rainbands. In section 4 a pair of papers by Emanuel gives a good theoretical introduction to symmetric instability. I would like to have seen a comparable treatment of the rest of frontal theory. The survey of cold air mass disturbances by Rasmussen is comprehensive and well illustrated. The next section on gravity waves is given a good theoretical introduction by Lilly and is followed up with some useful papers by Egger, although the first of these duplicates some of Lilly's material. It is unfortunate that Egger's paper on observations of flow in valleys which naturally follows his paper on topographic forcing was removed to the boundary layer section. The next section on buoyant convection is 250 pages in length and much the largest. A sequence of well written papers by Simpson traces the development of understanding, principally from the observational viewpoint. This is complemented in the next paper by Miller and Moncrieff who present the modeller's viewpoint. Several of the other papers in this section present valuable material but there is much duplication and little coherence. The boundary layer section also starts with two authors whose papers complement each other. Wyngaard takes an observational viewpoint while André concentrates on turbulence closure modelling. The remaining papers here are again rather disconnected and duplicate these first two. The final section on observational technology seems quite out of place. For instance, one feels that a discussion of the theory of wind retrieval from a Doppler radar is hardly relevant without some indications of how the results may be used.

To summarize: there is much valuable material in this book for both newcomer and established researcher in the field of mesoscale meteorology. However, the opportunity has not been taken to produce a textbook from the material and so, as with any conference proceedings, the reader will have to search for what he wants.

B. W. Golding

Hydrology in practice, by Elizabeth M. Shaw. 150 mm × 215 mm, pp. vii + 569, *illus.* Van Nostrand Reinhold Company Ltd, Wokingham, 1983. Price £18.50 (cloth), £9.75 (paper).

This book represents the culmination of the author's long career as a lecturer and researcher in hydrology. It has been primarily written as an introduction to the subject for undergraduate students of civil engineering and environmental sciences. Its scope is very widespread and, whilst presented from a British viewpoint, is set in a global context.

The book opens with an introductory chapter on the hydrological cycle and basic hydrometeorology. The remaining chapters are then grouped into three sections under the general headings: 'Hydrological measurements', 'Hydrological analyses' and 'Engineering applications'. The first section begins with the design of hydrometric networks and then goes on to describe the various methods available for measuring precipitation, evaporation, soil moisture, river and ground water flow, and water quality. The final chapter in the section deals with the processing of hydrological data; in particular that of rainfall and river flow. It is unfortuate, however, that the description given in this chapter of the Meteorological Office rainfall quality-control program actually refers to the version used prior to 1976. Readers who are interested in knowing about the methods currently being used by the Meteorological Office should refer to *Meteorological Magazine*, **104**, 102–108 (Computer quality control of daily and monthly rainfall data, by R. J. Shearman, 1975).

The second section covers the analytical treatment of hydrological data and includes chapters on precipitation and river flow analyses dealing with the fitting of frequency distributions and the calculation of exceedance probabilities from extreme-value statistics. This section also includes rainfall run-off relationships, catchment modelling and the use of time-series analyses. In addition there is a chapter on calculations of evaporation and soil moisture deficit which includes an explanation of the Meteorological Office Rainfall and Evaporation Calculation System (MORECS). Whilst the current operational model of MORECS is described in principle the model did undergo a few modifications whilst the book was in its final stages of preparation. For specific details readers should see *Hydrological Memorandum No. 45*, Meteorological Office, Bracknell (The Meteorological Office rainfall and evaporation calculation system: MORECS (July 1981), by N. Thompson, I. A. Barrie and M. Ayles, 1981).

The final section describes the application of hydrological analyses in the field of civil engineering. This includes chapters on flood routeing, design floods, urban hydrology and the management of river basins and water resources.

In order to cover a large portion of what is a vast subject the author has in general restricted herself to giving an overview of the various facets of hydrology rather than detailed discussions. However, for the reader who wishes to follow up particular aspects in greater depth references are provided at the end of each chapter, although in some cases these are rather too few in number.

This book should nevertheless prove a useful aid to anyone whose work requires a knowledge of hydrology and provides a useful introductory guide to the subject.

A. P. Butler

Books received

Energy at the surface of the earth: an introduction to the energetics of ecosystems, by D. H. Miller (New York, London, Toronto, Sydney and San Francisco, Academic Press, 1981. £14) is volume 27 in the International Geophysics series and presents one way of looking at the manner in which the biological, physical and cultural systems enable the land masses of our planet to receive, transform and give off

energy. The first part of the book deals with the radiant energy absorbed by ecosystems; the fulcrum chapter deals with the raising of surface temperature from the increase of such absorption and is followed by chapters on temperature-dependent fluxes of energy. The final chapters are concerned with vertical stratification and areal contrasts in energy budgets, the augmented energy budgets of the city, and the responses that serve to keep the budget balanced.

Chemistry of the unpolluted and polluted troposphere, edited by H. W. Georgii and W. Jaeschke (Dordrecht, Boston and London, D. Reidel Publishing Company, 1982. Dfl 145) is the Proceedings of the NATO Advanced Study Institute held on the island of Corfu, 28 September – 10 October 1981. The introductory Part I presents the problems and methods of measuring trace gases and aerosols; this is followed in Part II by the influence of the thermodynamic structure of the atmosphere on the transport and distribution of trace compounds and the interactions between trace compounds and climate. Part III deals with atmospheric cycles of some trace elements and compounds, Part IV with the fact that the troposphere is not a homogeneous gas phase, and Part V is concerned with the problems of pollution.

General hydrogeology, edited by E. V. Pinneker (Cambridge, London, New York, New Rochelle, Melbourne and Sydney, Cambridge University Press, 1983. £22.50) is from the Cambridge earth science series and is a translation by D. E. Howard and J. C. Harvey of a book originally published in Russian in 1980. The introductory section consists of the subject matter of hydrogeology, its definition as a science, an historical review and a discussion of terminology. The circulation of water in the earth and a description of ground water-bearing systems, distinguished according to the manner in which they are deposited, is then given. The book ends with chapters dealing with the features of hydrogeothermics and regional hydrogeological laws.

Severe and unusual weather, by Joe R. Eagleman (New York, Cincinnati, Toronto, London and Melbourne, Van Nostrand Reinhold Company, 1983. £22.50) is divided into three parts. The first includes, amongst others, frontal cyclones, blizzards and thunderstorms, and acquaints the reader with the nature of such events. The second part considers floods and droughts, in the main, and the final part weather simulation and management.

Sunsets, twilights and evening skies, by Aden and Marjorie Meinel (Cambridge, Cambridge University Press, 1983. £17.50, US $29.95) is a lavishly illustrated book describing twilight effects in the atmosphere for the general reader. It is the fruit of the authors' many years of personal experience and unites science and aesthetics in describing and explaining a subject of intrinsic beauty. Among the many topics covered are the earth's shadow and sunset phenomena, volcanic eruptions and twilights, zodiacal light and the aurora.

Award

We are pleased to record that Emeritus Professor H. H. Lamb of the University of East Anglia has been awarded the 58th Vega Medal of the Swedish Geographical Society. Professor Lamb was presented with the medal by Princess Christina of Sweden in Stockholm in April.

The Vega Medal, for significant contributions to geographical science, was first awarded in 1881 to Nordenskiöld, leader of an expedition with the SS *Vega* in 1878–79 through the North East Passage to the Pacific. Previous recipients include Nansen, Amundsen, Scott and Shackleton among explorers, and L. Dudley Stamp, Jacob Bjerknes and T. Bergeron among geographers and meteorologists. The citation recognizes Professor Lamb's 'pioneering contributions to the history of climate variations and their dependence on changes in the general atmospheric circulation'.

After more than 30 years' service in the Meteorological Office Professor Lamb left Bracknell at the end of 1971 for Norwich to direct the new Climate Research Unit that had been set up at the University. His many friends and ex-colleagues in the Office will wish to add their congratulations to the many others he has doubtless received.

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NOTICE

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ and marked 'For Meteorological Magazine'.

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